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H I in HO: Hoag's Object revisited

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ABSTRACT

We present new H I observations of Hoag's Object (HO) obtained with the Westerbork Synthesis Radio Telescope. The data show that the luminous optical ring around the elliptical body has a bright H I counterpart that shares the kinematical properties of the optical ring. The entire H I structure is twice as large as the optical ring and shows a mild warp in its outer regions relative to the inner ring. We detect two additional H I sources close in redshift to that of HO, and report on a newly identified SDSS optical companion galaxy. The H I sources are ∼0.3 and ∼1 Mpc away in projected distance, and the companion galaxy is also ∼1 Mpc away. Our main conclusion is that the H I detected in HO shows no indication that this galaxy has experienced a recent (less than ∼1 Gyr ago) accretion event. At least one of the two additional H I detected objects does not have an optical counterpart. One possibility is that this object is an H I filament left over from an interaction shaping HO, in which case this interaction must also have occurred at least 1–2 Gyr ago.

Key words: galaxies: individual: Hoag's Object.

1 INTRODUCTION

Hoag's Object (HO) is an intriguing galaxy. Discovered by Hoag (1950), it was the topic of few research papers in the last six decades despite being the most perfect ring galaxy known today. While Hoag suggested that this could be a case of gravitational lensing since the ring seemed perfect on the 24-inch Jewett Schmidt telescope plates he examined, O'Connell, Scargle & Sargent (1974) ruled out the lensing hypothesis by arguing that, in this case, the central object should have a mass-to-light ratio of 1500 $M_\odot/L_\odot$.

Brosch (1985) studied optical images of HO obtained at the Wise Observatory and H I synthesis observations with the Westerbork Synthesis Radio Telescope (WSRT). The optical data showed that the central object has a de Vaucouleurs ($r^{1/4}$) profile and that the ring's surface brightness was significantly brighter than the extrapolated brightness of the central object at the same radius. The 12-hour synthesis H I observations were unsuccessful, yielding a 3σ upper limit of 2.9 mJy over 33 km s^{-1}. Thus, only an upper limit of 2.3×10^9 $M_\odot$ could be set for the total H I content for an unresolved H I object at the position of HO. Brosch proposed that HO was the result of star formation induced in a gaseous ring around an object similar to an elliptical galaxy that had a bar, which almost relaxed back into the central object.

Schweizer et al. (1987) presented optical observations with the Palomar 5-m telescope and with the Arecibo radio telescope. Their optical spectroscopy ruled out the gravitational lensing suggestion by showing that the ring and the central object are at the same redshift. The 21-cm Arecibo observations showed a two-horned profile with a width of 239 km s^{-1} and a flux integral of 1.15 ± 0.10 Jy km s^{-1} centred on the optical redshift, from which Schweizer et al. concluded that HO contained $(7.0 \pm 0.1) \times 10^9$ $M_\odot$ of H I (converted to our assumed distance of 175.5 Mpc using $H_0 = 73$ km s^{-1} Mpc^{-1}). They proposed that HO was the result of a major accretion event at least 2–3 Gyr in the past.

Finkelman et al. (2011) analysed *HST* archival observations and optical spectroscopy, including two-dimensional scanning Fabry–Perot interferograms of the Hα line, obtained at the Russian Academy of Sciences 6-m BTA telescope. The *HST* images confirmed that the inner body has indeed a de Vaucouleurs surface brightness profile. The central object has the appearance of a slightly triaxial elliptical galaxy, and the spectroscopy showed that it is a fast rotator.

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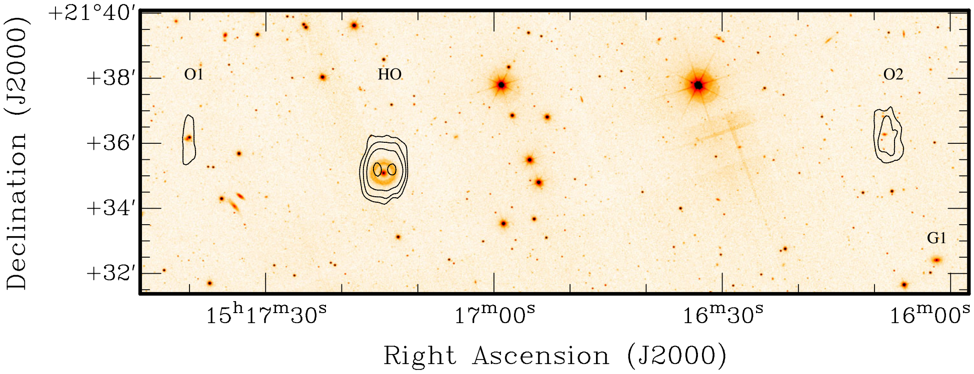

Figure 1. The field of HO from the SDSS *r*-band image, with superposed H I contours and various objects labelled. The contour levels are (3, 6, 12 and 24) $\times\ 10^{19}$ cm^{-2}. The companion H I cloud O1 is to the left-hand side of HO and the second H I companion, O2, is near the right-hand edge of the plot. More detailed plots for each of the sources are shown in Figs 2 (HO), 5 (O1) and 6 (O2). A newly identified neighbour galaxy (see below) is marked G1 at the lower right-hand corner of the image.

Finkelman et al. (2011) found that the ionized gas kinematics (in the ring) could be fitted with a circular rotation model, with its equatorial plane inclined relative to the line of sight by $18° \pm 4°$. The ring was restricted to radii $14 \le r \le 28$ arcsec and various fitting attempts indicated that non-circular motion is present there in addition to the circular motion. The ring showed a braided quasi-spiral structure of H II regions. Population synthesis of observed optical spectra showed that the core object is older than 10 Gyr, while the ring's stellar population is ∼1 Gyr, sustaining a low level of star formation at a rate of $\sim 0.7\ \mathrm{M_{\odot}\ yr^{-1}}$. The age of the stellar population in the ring was derived from a luminosity-weighted single stellar population, thus not excluding the presence of stars significantly older than 1 Gyr. Finkelman et al. (2011) proposed that a large H I mass was accreted soon after the formation of the elliptical core. The H I settled into a disc which now shows star formation triggered by the mild triaxiality of the core. Given the current star formation rate and the Arecibo-detected H I content, HO could remain in a quasi-steady state for a Hubble time.

H I observations provide a complementary method to optical observations at revealing past interactions and possibly accretion events, since at very large radii, where H I is often found but the ionized gas component is weak or absent in the optical range, the kinematic time-scales are long. Nevertheless, relatively little effort has been spent on studying the gas properties of HO, with the exceptions of Brosch (1985) and Schweizer et al. (1987) mentioned above.

While the optical appearance of HO seems now reasonably well understood, the questions are where in relation to the luminous galaxy is the H I detected by Schweizer et al. (1987), how is this H I distributed, and what are its kinematic properties. The presence or absence of morphological or kinematical irregularities in the H I distribution can provide essential inputs for evolution models of this object, thus determining its place among other galaxies. To understand HO better we performed synthesis H I observations at the WSRT, expecting that these would enable the study of both the neutral gas distribution and the H I kinematics. The optical ring of HO has a diameter of about 40 arcsec, thus the WSRT is well suited to spatially resolve the ring while still maintaining good column density sensitivity. We show here that the H I is arranged in a ring significantly larger than the optical one, is slightly warped at its outer regions, and contains at least $6.2 \times 10^{9}\ \mathrm{M_{\odot}}$ of H I.

The structure of this paper is as follows. In Section 2, we describe the observations and their reductions. Section 3 details the reduction process, which had to be somewhat different from the standard WSRT reductions to reveal faint H I details near HO. The results are detailed in the same section, and we present in Section 4 a discussion where HO is discussed in the context of other ringed galaxies. Section 5 summarizes this paper.

2 OBSERVATIONS AND DATA REDUCTION

HO was observed for $4 \times 12{+}6$ h (54 h total) with the WSRT in the maxi-short configuration, with a 36 m shortest baseline. The setup used a 20 mHz band centred on 12 736 km s^{-1} split into 1024 spectral channels, with the two orthogonal polarizations averaged.

The data were calibrated in the standard way, using the MIRIAD package (Sault, Teuben & Wright 1995). We used the data to make two data cubes, one using standard weighting (robust = 0.4) to image the kinematics of the H I, and another cube made with natural weighting to have maximal sensitivity for detecting faint H I structures in the vicinity of HO. The velocity resolution of these data cubes is 8.8 km s^{-1}. The beam of the standard cube is 16×45 arcsec (half-power beam width) and this cube has a 5σ column density detection limit of 2.6×10^{19} cm^{-2} over 20 km s^{-1} and a mass detection limit of $1.2 \times 10^{8}\ \mathrm{M_{\odot}}$ over 20 km s^{-1}. The 5σ column density detection limit in the naturally weighted cube is 1.4×10^{19} cm^{-2} over 20 km s^{-1}. This sensitivity is one order of magnitude better than that of the 1982 WSRT observations (Brosch 1985).

3 ANALYSIS AND RESULTS

Fig. 1 shows the optical image from SDSS with superposed H I contours from the standard-weighting map, detailing the detection of H I in HO and in two objects in its vicinity. The figure shows that the H I is well detected in HO. The results for HO are shown in better detail in Fig. 2, where the top panel shows an SDSS image with the H I contours overlaid. The synthesized beam is shown at the lower left-hand corner of this figure. The derived HO flux integral is 0.86 Jy km s^{-1} which, for a distance of 175.5 Mpc, gives $M(\mathrm{H\,I}) = 6.2 \times 10^{9}\ \mathrm{M_{\odot}}$ with an uncertainty of 10 per cent. It is clear that the H I coincides with the optical ring and that no H I is detected inside it.

The H I distribution appears to have two maxima, east and west of the optical centre. This is an artefact caused by the beam which is elongated in the north–south direction, since the observations were made with a linear antenna array oriented in the east–west direction.

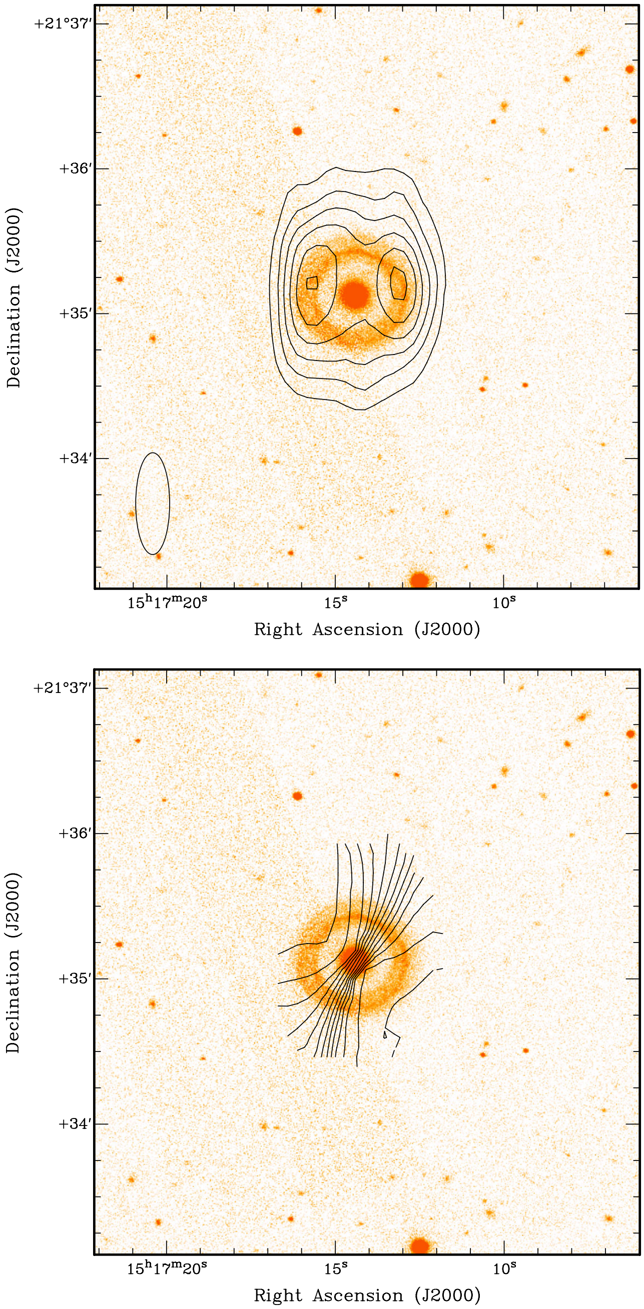

Figure 2. Hoag's Object in H I. Top panel: the H I contours overplotted on the SDSS *r*-band image. The synthesized beam is plotted at the lower left-hand corner. The contours plotted are (5, 10, 15, 20, 25 and 30) × 10^{19} cm^{-2}. Bottom panel: the VF of Hoag's Object. The lowest contour is at 12 670 km s^{-1} and the step between consecutive contours is 10 km s^{-1}. The lowest velocity is at the lower right-hand side of the plot.

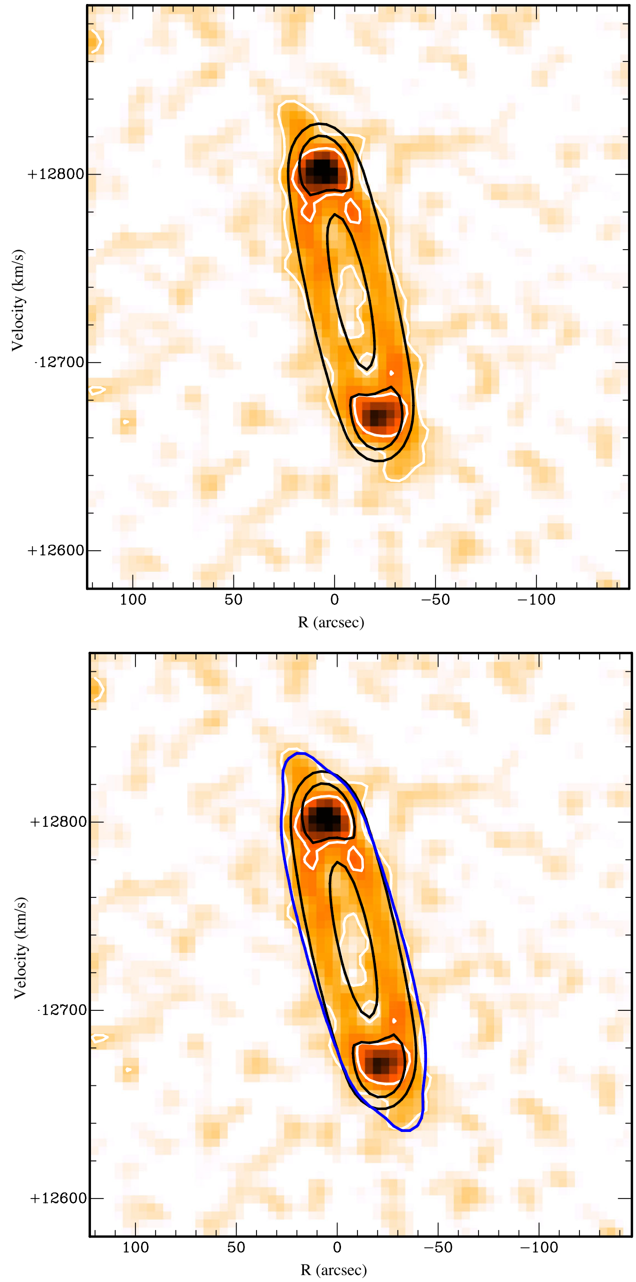

Figure 3. Models fitted to the H I distribution in HO. Top panel: single-ring fit, with the equatorial plane of the ring tilted 18° with respect to the line of sight. Bottom panel: two-ring fit with the outer ring tilted by 7° with respect to the inner ring and with the same rotational velocity.

A model of a uniform ring convolved with the synthesized elongated beam yields exactly the observed structure. The H I distribution is definitely more extended than the optical image of the ring, perhaps twice as wide. On the other hand, the H I map does not show tails or extensions, as could have been expected were the H I recently acquired via a tidal interaction.

The lower panel of Fig. 2 shows the velocity field (VF) overplotted on the HO optical image. The VF was produced by fitting Hermite Gaussians to those profiles where the H I column density was above 5 × 10^{19} cm^{-2}. The VF appears quite regular, with no obvious disturbances, and is another argument against a recent interaction being the source of the H I.

Using the parameters of the kinematics of the optical data from Finkelman et al. (2011), we constructed H I model cubes for HO using TIRIFIC (Tilted Ring Fitting Code; Józsa et al. 2007). Basically, the first model is a single ring of the same size as used in the modelling of the ionized gas VF (radii 14–28 arcsec) of inclination ∼18° and using the same rotation velocities as Finkelman et al. The top panel of Fig. 3 shows a position–velocity plot (not aligned with the major-axis but along constant declination) of the model and the data. The figure shows that the model reproduces the data fairly

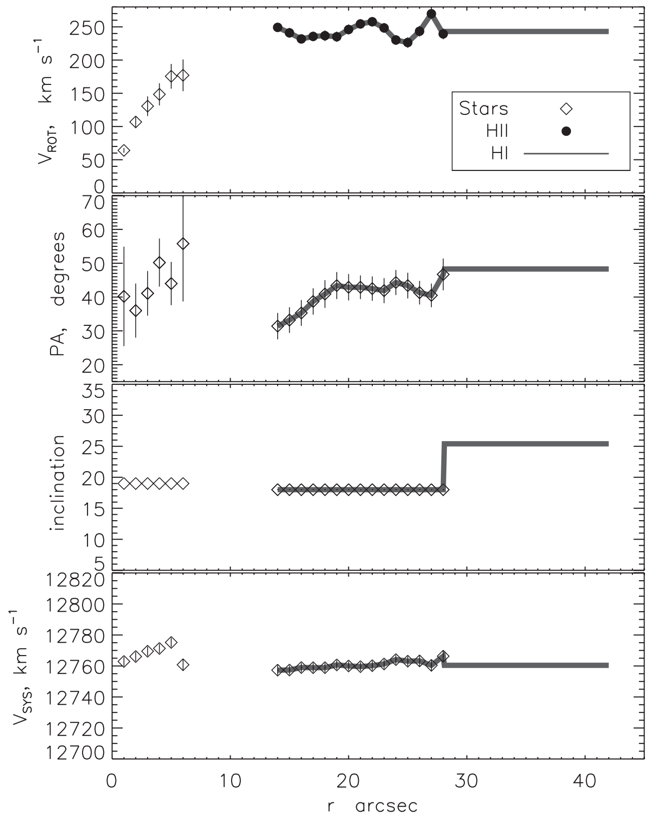

Figure 4. Joint optical–H I plot describing the variation in the kinematical properties of HO. The parameters shown versus radius are the rotational velocity (top), position angle (second from the top), inclination (second from the bottom) and systemic velocity (bottom).

well, except for the faint extensions at the most eastern and western sides of the ring, at velocities away from the systemic velocity.

These H I extensions suggest that the H I ring extends beyond the optical ring, but at lower column densities compared to the inner H I. We modelled this by extending the previous model with a second ring covering radii between 28 and 42 arcsec. Given the approximately face-on orientation of the H I in HO and the limited spatial resolution, it is difficult to obtain a sensible result using a free fit of all parameters. Therefore, we assumed that the rotation curve of HO is flat out to the outermost radii. Given that the outer H I has larger projected rotation velocities, the outer ring has to have a slightly higher inclination than the inner H I.

We obtain a satisfactory model by using an inclination for the outer H I ring of 25°, or 7° more than that of the inner ring. The bottom panel of Fig. 3 shows the position–velocity plot of this model, illustrating that this model describes the data quite well. The small inclination increase with radius implies that the H I ring in HO is slightly warped at large radii. Such warps are a common feature in any galaxy with an H I disc extending beyond the optical disc, including early-type galaxies with H I discs. Fig. 4 summarizes the parameters of our final kinematical model, implying that in HO we see a stellar ring with a diameter of ∼47 kpc embedded in and surrounded by an ∼71 kpc wide H I ring.

The results discussed above are based on an H I cube made with standard weighting. We also made a naturally weighted cube to search for faint emission around HO. In this data cube, we detect two additional H I sources, very faint, near the redshift of HO, that are also plotted in Fig. 1. A few more galaxies are detected in the data, but these have systemic velocities about 1000 km s^{-1} lower and are most likely not related, thus have not been plotted in the figure. The two sources possibly associated with HO are called here Object 1 (O1) and Object 2 (O2). The parameters of these companion objects are given in Table 1. These are very faint detections, not visible in the data cube with standard weighting because the signal is diluted by a large linewidth (see Fig. 3). However, because of their extent, they contain considerable amounts of H I.

Table 1. Objects in the HO complex.

Object/parameter	HO	O1	O2	G1
α J2000	15:17:14	15:17:40	15:16:09	15:16:01
δ J2000	+21:35:08	+21:36:19	+21:36:10	+21:32:27
$cz_{\odot}$ (km s^{-1})	12736	12700	12629	12676
M(H I) (10^9 M$_{\odot}$)	6.2	0.39	1.2	–

Note: Object G1 is the companion galaxy mentioned in the text and marked in Fig. 1 which does not have detectable H I.

SDSS *r*-band images with overplotted H I contours for O1 and O2 are shown in Figs 5 and 6, respectively. Fig. 5 shows the total H I of O1 in the top panel and a position–velocity plot at constant declination in the bottom panel. Fig. 6 shows O2, for which the H I signal is too faint to produce a useful position–velocity plot. Both objects seem to have faint optical counterparts within the synthesized beams, as shown in Figs 5 and 6. SDSS reports an object at each of the locations and near O1 there is also a star.

The diffuse object in the immediate vicinity of O1 and adjacent to the bright star is the galaxy SDSS J151740.21+213609.7 which has a well-established spectroscopic redshift of $z = 0.143$, implying that it is a background object not related to HO. The diffuse object near the centre of O2 is the galaxy SDSS J151608.49+213618.4, which lacks a redshift. However, its apparent magnitude and colours, $r = 18.65$ and $(g - r) = 0.34$ with $(r - i) = 0.22$, put this object in the 'green valley' location, if at the distance of HO. Other SDSS objects near the H I locations of O1 or O2 also do not have optical spectral information but have bluish colours and the appearance of dwarf galaxies.

4 DISCUSSION

We mentioned in the Introduction that Schweizer et al. (1987) measured a flux integral of 1.15 Jy km s^{-1} with Arecibo, whereas we measure only 0.86 Jy km s^{-1} from the synthesized map. These values are consistent, given their errors, and since the WSRT configuration, with a smallest baseline of 36 m, did not miss much widespread H I.

Finkelman et al. (2011) found no observational evidence to support late-merging events in the evolution of this galaxy; the main stellar body was found to be at least 10 Gyr old and deep optical images from the 6-m BTA telescope did not reveal faint tidal tails or low surface brightness features around the galaxy, up to a projected distance of ∼150 kpc. The main result of the present paper is that, in the WSRT data shown here, we do not see any *direct* evidence for an accretion event. The H I does extend somewhat beyond the optical ring, but the kinematics are regular. The orbital time at the outer edge of the optical ring is $\sim 6.7 \times 10^8$ yr and this is of the order of the crossing time τ; since the relaxation time for a gas system is a few τ, the lack of disturbances in the H I suggests that HO has not experienced a major accretion event in the last 1–2 Gyr.

Finkelman et al. (2011) argued that, since the nearest neighbour to HO with an optically measured redshift was about

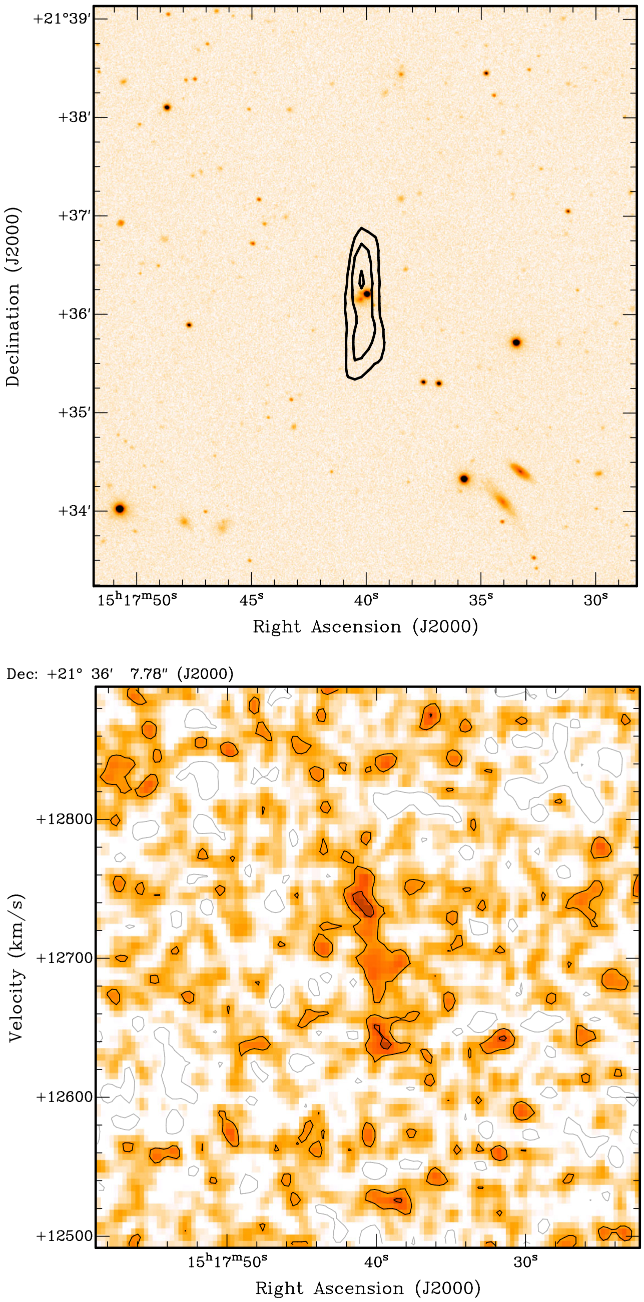

Figure 5. H I companion of HO, called here O1 and detected using natural weighting of the WSRT channels. Top panel: the H I contours of O1 overplotted on the SDSS *r*-band image. The contours plotted are (3, 4 and 5) $\times$ 10^{19} H-atoms cm^{-2}. Bottom panel: a velocity–right ascension plot of O1. The contours plotted are -0.33, 0.33, 0.66 mJy beam^{-1}.

3 Mpc away, HO must be a relatively isolated galaxy. A repeated search of the HO neighbourhood using the NASA/IPAC Extragalactic Database (NED) revealed a closer companion: 2MASX J15160166+2132270 = SDSS J151601.65+213226.6, called here G1, with an SDSS DR9 redshift of 12676 km s^{-1}. The galaxy is visible near the lower right-hand corner of Fig. 1 as a fuzzy elliptical blob. Inspecting the SDSS DR9 data shows an Sa shape and an absorption line spectrum. The SDSS absolute magnitude $M_r = -20.33$ and colour $(r - i) = +0.87$ puts this object in the 'red-sequence' location of the colour–magnitude plot for galaxies. This is also supported by the SDSS spectrum which does not show emission lines that could be associated with star formation. The newly reported optical companion is 17.2 arcmin = 877 kpc projected distance and 60 km s^{-1} away from HO, and only ∼100 kpc and 42 km s^{-1} from the O2 H I cloud.

The two H I companions reported here, O1 and O2, are at ∼300 kpc and ∼1 Mpc projected distances, respectively, from HO. It is clear that all four bodies form a single complex, although no signs of ongoing mutual interactions are visible. It is interesting that O1 does not have an optical counterpart, despite having a reasonably wide H I line (∼140 km s^{-1}, see the bottom panel of Fig. 5). Assuming a simple Tully–Fisher relation, such a linewidth would imply an absolute magnitude of about –17, thus an apparent magnitude of ∼19, only slightly fainter than SDSS J151740.21+213609.7 that could mask its presence.

The optical counterpart of O1 could be a hidden dwarf galaxy, or this may mean that the H I in O1 could be the remnant of some galaxy–galaxy interaction, possibly one involving HO. Given its separation from HO, and assuming relative velocities of 200 km s^{-1}, such an interaction could have occurred not more recent than ∼1–2 Gyr ago.

We have shown in Fig. 1 that HO and its two H I cloud companions are located on an approximately straight linear structure. The optical companion galaxy G1, O1 and HO lie actually on an even straighter line. This situation, of some optical galaxies and H I clouds being arranged in a linear shape, is reminiscent of the finding of Beygu et al. (2013). They argue that a galaxy triplet is growing along a filament in a void in the galaxy distribution, from H I it concentrates out of the intergalactic medium. Other similar linear structures were detected by Zitrin & Brosch (2008).

Regarding the morphological peculiarity of HO, the observations reported here and in Finkelman et al. (2011) support an interpretation that HO is another ringed galaxy where, by chance, we observe the gas-and-stars ring approximately pole-on, orbiting in or near the equatorial plane of the central body with its outer parts being slightly warped. Such a configuration, where an outer star-forming ring surrounds an early-type galaxy, is reminiscent of the outer ultraviolet (UV) discs observed around lenticular galaxies, by, e.g. Ilyina & Sil'chenko (2011), which sometimes appear as UV-bright rings (XUV rings). In fact, ESO 381−47, which is an S0 galaxy with a faint 30-kpc-wide stellar ring and a much wider 90-kpc H I ring, seems to be very similar to HO but at 61.2 Mpc is much closer (Donovan et al. 2009). The difference, in this case, is that while the objects discussed by Ilyina & Sil'chenko and by Donovan et al. are early-type discs, Finkelman et al. (2011) showed that the central object of HO matches a triaxial elliptical classification.

In this context, we mention that very large, regular H I structures are sometimes encountered around fairly isolated early-type galaxies (Oosterloo et al. 2010; Serra et al. 2012), and many of these structures are warped. It is clear that HO belongs to the class D galaxies, 'where most of the H I is found in a fairly regularly rotating disc or ring' (Oosterloo et al.), best shown by NGC 3945 of morphological type (R)SB0, and NGC 5582 (type E) in Serra et al. (2012).

This paper adds one more object to the set of early-type galaxies with outer rings of stars and H I. Here too, as in the other cases, the origin of the gas is not clear-cut. This could be an early accretion event, ∼10 Gyr ago as suggested by Finkelman et al. (2011) but not later than a few Gyr ago, or could be ongoing galaxy formation with gas accreted from the cosmic web which is manifested not only as HO's ring, but also as the O1 and O2 objects, although no observational evidence for that exists at present.

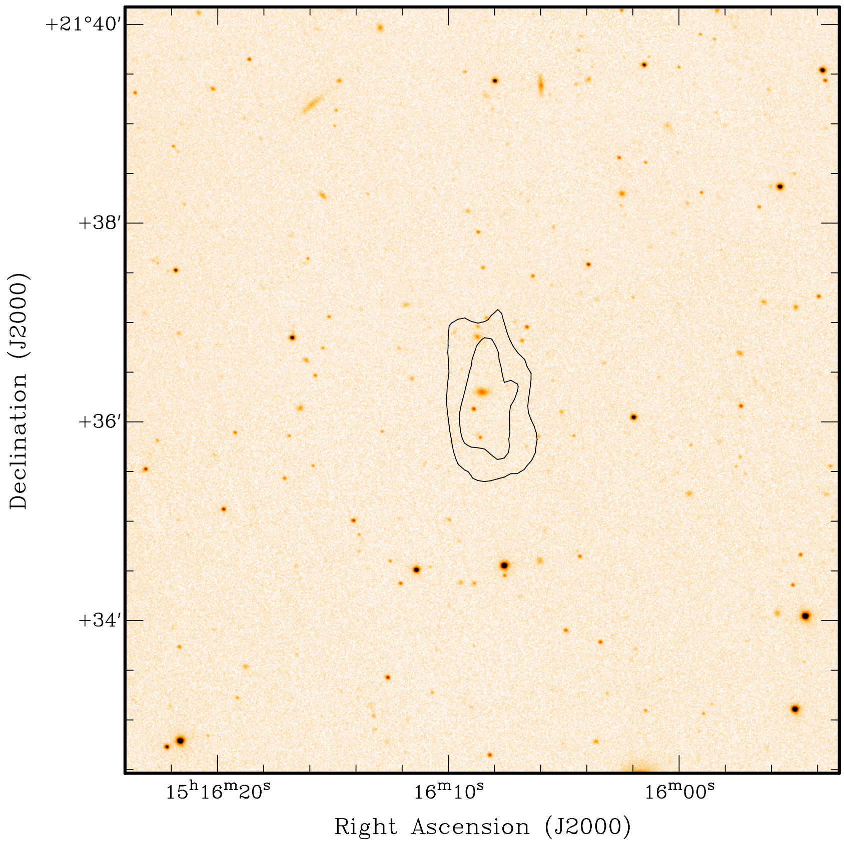

Figure 6. H I companion of HO, called here O2 and detected in the same manner as O1. Contours on the levels of (3 and 6) × 10^{19} H-atoms cm^{-2} plotted on the SDSS *r*-band image.

5 SUMMARY

We presented H I synthesis observations of HO obtained with the WSRT. These show that HO has an H I ring containing ~6 × 10^9 M$_\odot$ of H I that extends beyond the optical ring of this galaxy. The H I shares the kinematics of the optical ring. Outside the optical ring, the H I ring shows a slight warp. The kinematics of the H I are very regular, and there is no indication that HO experienced a recent accretion event. From the kinematics of the H I we conclude that any accretion event could have happened no later than 1–2 Gyr ago.

We identified an optical companion that is an early-type disc ~1 Mpc away in projected distance, and two 21 cm clouds, one at ~300 kpc and containing ~4 × 10^8 M$_\odot$ of H I and the other more distant (~1 Mpc) with ~10^9 M$_\odot$ of H I, at least one of the clouds lacking a confirmed optical counterpart. All four bodies may be part of an approximately linear structure extending over ~1.5 Mpc, in the outskirts of a loose grouping of some 60 galaxies about 3–6 Mpc away.

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REFERENCES

Beygu B., Kreckel K., van de Weygaert R., van der Hulst J. M., van Gorkom J. H., 2013, AJ, 145, 120
Brosch N., 1985, A&A, 153, 199

Donovan J. L. et al., 2009, AJ, 137, 5037
Finkelman I., Moiseev A., Brosch N., Katkov I., 2011, MNRAS, 418, 1834
Hoag A. A., 1950, AJ, 55, 170
Ilyina M. A., Sil'Chenko O. K., 2011, Astron. Lett., 37, 589
Józsa G. I. G., Kenn F., Klein U., Oosterloo T. A., 2007, A&A, 468, 731
O'Connell R. W., Scargle J. D., Sargent W. L. W., 1974, ApJ, 191, 61
Oosterloo T. et al., 2010, MNRAS, 409, 500
Sault R. J., Teuben P. J., Wright M. C. H., 1995 in Shaw R. A., Payne H. E., Hayes J. J. E., eds, ASP Conf. Ser. Vol. 77, Astronomical Data Analysis Software and Systems IV. Astron. Soc. Pac., San Francisco, p. 433
Schweizer F., Ford W. K., Jr, Jedrzejewski R., Giovanelli R., 1987, ApJ, 320, 454
Serra P. et al., 2012, MNRAS, 422, 1835
Zitrin A., Brosch N., 2008, MNRAS, 390, 408

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